ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.2575

Sustainable technical-production model (bioeconomy) for the cultivation of *Chondracanthus chamissoi* in La Libertad (Perú)

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***Abstract*– This research develops a technical-production model for the cultivation of Chondracanthus chamissoi (Yuyo) in the La Libertad region of Peru. Socioeconomic, environmental, and extractive pressure factors on natural beds were integrated. Primary information was obtained from the La Ramada Artisanal Fishermen's Association (APDAR), along with laboratory data on vegetative propagation and suspended systems, and evidence of macroalgae harvesting dynamics according to the DPSIR framework. The results showed that implementing in-line cultivation systems achieves controlled production, reduces pressure on natural resources, and generates added value. The financial evaluation indicates the need for scaling up and product diversification to achieve profitability. This model contributes to strengthening community governance and blue bioeconomy strategies.**

***Keywords*--Chondracanthus chamissoi, suspended culture, vegetative propagation, sustainable aquaculture, DPSIR, community governance**

I. Introduction

In some regions worldwide, seaweed mariculture has emerged a strategic, high-yield activity, not only from a nutritional perspective but also in economic terms. It does not require arable land or freshwater resources, which represents a significant advantage for the development of a sustainable bioeconomy while contributing to food security [1]. In South America, many artisanal fishing associations lack access to technical assistance and financial support to sustainable development. Although red algae are underexploited globally, they have significant commercial potential. *Chondracanthus chamissoi,* distributed along the South American coast, especially between Peru and Chile, is traditionally consumed in the region. In Peru, its harvesting fluctuates and is intensively exploited by artisanal fishers as a source of income. However, overexploitation and limited cultivation technologies raise concerns about its long-term sustainability [2].

Fishers typically harvest seaweed in intertidal zones during periods of peak seasonal abundance, making them highly dependent on seasonality. The lack of cultivation techniques limits productivity and profitable production. Advances in vegetative propagation under controlled conditions have enabled the development of sustainable production models in coastal environments, highlighting the need for technical, economic, and environmental feasibility studies [3]. This approach promotes the growth and regeneration of *Chondracanthus chamissoi* after harvesting. Suspended culture systems achieve higher biomass yields compared to bottom cultures [2]. This technologically advanced activity enhances commercial practices focused on the nutritional value of red algae. International demand compels decision-makers to promote sustainable production systems to ensure food security and maintain a continuous supply, generating income for artisanal fishers governed by local or regional associations.

Recently, [4] reported that this species contains proteins, minerals, and bioactive compounds such as polysaccharides (carrageenans) and antioxidants, whose technological exploitation presents potential for the food and pharmaceutical industries [5]; in the hands of artisanal fishers, it contributes to circularity, resource valorization, and reveals opportunities to diversify production with greater added value [5]. Furthermore, sustainable algae aquaculture mitigates pressure on natural beds, generating added value and strengthening local production chains [6].

The La Libertad region in northern Peru is characterized by the artisanal harvesting of the seaweed *Chondracanthus chamissoi*, which grows along intertidal zones composed of rocks and sand where extensive seagrass meadows have formed. Although natural beds are present year-round, September and February are the months of greatest availability [7]. This activity is important for coastal communities [8].

High harvesting levels, overexploitation, and pressure on coastal ecosystems [9], together with environmental variability caused by ENSO events and seasonal river flows, generate fluctuations in algal biomass and density, affecting fishers' income and employment [8]. Recent studies show that the extractive fishery of *C. chamissoi* is strongly influenced by socio-economic and natural forces [8]. Atoche et al. [8] applied a DPSIR model to identify socio-economic and environmental pressures on natural beds and artisanal exploitation. Efforts are underway to develop laboratory propagation of *C. chamissoi* in La Ramada [11], followed by sea cultivation, reducing extraction pressure. Arbaiza et al. [3] improved vegetative propagation using fixation discs with *Argopecten purpuratus*, increasing inoculum production and optimizing culture scaling.

In this context, this research proposes the implementation of a technical-productive model for the La Ramada Artisanal Fishermen's Association (APDAR). This sustainable and comprehensive model, based on a bioeconomy approach for

Chondracanthus chamissoi, integrates vegetative propagation under controlled conditions, complemented by suspended sea cultivation, community involvement, and management of macroalgae extraction pressure. It also includes financial evaluation and sales projections. This methodology has been applied to the artisanal fishing associations of La Ramada in La Libertad, where studies of natural beds and extraction pressure have been conducted. The aim is to transition from a traditional seasonal extraction system to a continuous production model that minimizes pressure on natural beds while meeting local and regional demand for red algae.

A. Technological Development and Value Chains for Added Value

The concept of biorefinery applied to algae proposes the comprehensive utilization of its biochemical fractions, maximizing economic performance and reducing waste, in accordance with the principles of industrial sustainability and the circular economy [12]. The economic viability of these systems depends on extraction efficiency, compound stability, and proper integration into the supply chain. In the case of *C. chamissoi*, recent studies have shown emerging applications in animal feed, improving productive and physiological parameters and expanding its market potential beyond traditional human consumption [13]. This reinforces the need to develop structured value chains that enable the diversification of its industrial use.

B. Environmental Sustainability and Ecosystem Services

Beyond its economic relevance, macroalgae aquaculture contributes significantly to ecosystem services such as carbon sequestration, dissolved nutrient removal, and improved water quality in coastal systems. These environmental benefits position algae as natural tools for climate change mitigation and adaptation strategies [6]. Integrating sustainable farming systems with value-added strategies not only generates commercial opportunities but also strengthens the socio-ecological resilience of coastal communities, reducing pressure on natural ecosystems and aligning with global sustainability goals.

C. Chondracanthus chamissoi: Biology, Traditional Use, and Productivity Gap

Chondracanthus chamissoi is a red macroalga distributed along the Pacific coast of South America, particularly in Peru and Chile. Recent analyses of the *C. chamissoi* fishery under the DPSIR framework have identified high local economic dependence, informal harvesting practices, and environmental variability as factors that increase the vulnerability of the resource and associated communities [9]. In parallel, experimental research in Peru has demonstrated the technical feasibility of vegetative propagation and controlled cultivation of *C. chamissoi* under natural marine conditions, obtaining favorable growth rates [3], [11]. These results support the implementation of continuous cultivation systems as an alternative to reduce dependence on natural beds. From a socio-economic perspective, managed cultivation and the incorporation of industrial transformation processes would stabilize supply, generate more sustainable income, and strengthen local value chains, contributing to the productive diversification of coastal communities

D. Extraction Pressure and Dynamics of the Chondracanthus chamissoi Resource under DPSIR

The *C. chamissoi* resource on the northern coast of Peru is subject to high extraction pressure, characterized by interannual fluctuations in biomass and density, influenced by natural (river flows, sedimentation, ENSO events) and anthropogenic factors (number of fishers, market pressure) [8]. This dynamic generates economic and social impacts, including variable incomes and conflicts associated with informality, affecting resource sustainability. DPSIR analysis identified driving forces, pressures, state, impacts, and responses associated with this system [8]. Applied to *C. chamissoi*, Atoche-Suclupe et al. [8] defined the following components: a) Driving forces, an increase in the number of fishers, domestic demand, and price variability influencing extractive pressure; b) Pressure: fishing effort and environmental processes affecting biomass availability; c) State: interannual fluctuations in density and biomass; d) Impact: economic losses and increased informality generating social tensions; and e) Response: community self-regulation and limited regulatory frameworks representing partial mitigation. Integrated management strategies are required to control extractive pressure and promote alternative cultivation methods.

E. Justification for Suspended Culture

The background described shows that the natural resource exhibits high variability and a limited capacity for self-regeneration under extraction pressure. Therefore, the implementation of long-line suspended culture systems is proposed as an alternative to guarantee a constant supply of *C. chamissoi* biomass; reduce pressure on natural populations; and integrate the socioeconomic dimension through the participation of associations such as APDAR. This diagnosis demonstrates that current extractive management does not effectively mitigate ecological and socioeconomic impacts, thus requiring an alternative approach that integrates sustainable production and community participation.

II. METHODS

1) Research Design: An applied, non-experimental research approach was used, combining primary data collection in APDAR (interviews, surveys, and observation); laboratory data on vegetative propagation and growth in suspended systems; a literature review on extractive pressure and DPSIR [6], [8]; and a prospective economic evaluation and income projection.

2) Technical-Productive Model: The proposed technical-productive model is based on previous studies by Soto-Deza et al. [11], who designed a long-line suspended culture system adapted to the coastal area of La Ramada, with units inoculated using SADs (spore adhesion discs). The vegetative propagation and formation of these units in the laboratory follow previously published methodologies for the species, ensuring their viability and growth to commercial size [11].

This scientific basis guarantees the biological and technical feasibility of the proposal. The model is structured in four main components: a) Marine cultivation system: Suspended long-line systems are used, with 100 thallus fragmentation per system. The production cycle is 2–3 months per season, with constant monitoring of fouling and nutrients to maintain optimal growth conditions. b) Harvesting and conditioning process: The biomass is harvested when it reaches a commercial size of over 8 cm. The production flow includes: extraction of seedlings in the laboratory, inoculation in suspended cultivation units, transfer to the open sea, growth to commercial size, harvesting, drying, and classification of the biomass for sale. c) Basic processing: This includes conditioning the biomass for direct sale and its potential industrial processing, ensuring quality and efficient marketing. d) Community organization: Fishermen are integrated through the La Ramada Artisanal Fishers' Association (APDAR), promoting technical training, formalization of the activity, and active community participation in all stages of the production process.

The operational flow of the model can be detailed in the following stages: 1) Maintenance and formation of SADs in the laboratory: Vegetative fronds of *C. chamissoi* are maintained in fertilized media until SADs form on natural (such as mollusk shells) or artificial substrates. 2) Inoculation and preparation of culture units: The units with SADs are transferred to long-line suspended systems. 3) Open-sea growth: The cultures are grown until they reach commercial size (≥8 cm). 4) Harvesting and post-harvesting: The harvested biomass is prepared for local or industrial marketing, including drying and grading.

TABLE I
Production process flow

Stage	Activity	Details
1	Formation of SADs	Vegetative fronds in fertilized medium until they form discs on natural or artificial substrates
2	Inoculation	Transfer of SADs to long-line type cultivation units
3	Growth	Open sea cultivation to commercial size ≥8cm
4	Harvest	Biomass collection according to production cycle (2–3 months)
5	Postharvest	Drying, sorting, and packaging for sale
6	Marketing	Local or industrial sales; potential added value

The technical-production system is based on the following key parameters: Type of cultivation (suspended long-line system); propagation method (vegetative propagation through thallus fragmentation) [14]; production cycle (2–3 months per season); environmental conditions (coastal area of La Ramada, with monitoring of fouling and nutrient availability); and operational stages (seedling extraction in the laboratory, inoculation in suspended cultivation units, growth in long-line systems using 100 thallus fragments per line, harvesting upon reaching commercial size, drying, classification, and conditioning for the final product). This comprehensive approach ensures the biological, technical, and economic viability of the cultivation, while promoting the integration and direct benefit of the region's artisanal fishers.

3) Economic evaluation: This considers initial investment criteria, including infrastructure, cultivation systems, and laboratory facilities; operating costs such as labour, maintenance, and logistics; estimated production (480–9600 kg/bacth, depending on batch and season); and the projected price per kilogram depending on season (Table 2).

TABLE II
initial investment and estimated operating costs (USD)

Concept	Estimated amount (USD)	Observations
Cultivation infrastructure	800 $	Longlines, substrates, floats
Laboratory and equipment	667 $	Preparation of SADs, culture media
Annual labor costs	533 $	Includes maintenance and operation
Maintenance and logistics	400 $	Transportation, line cleaning, monitoring
Total initial investment	2400 $	-

The following indicators, commonly used in community production project evaluation, were applied: net present value (NPV), internal rate of return (IRR), benefit–cost ratio, and break-even point. A discount rate of 9% was used. The five-year cash flow projection included the initial investment, operating costs, annual production levels, and projected selling prices.

4) Components of the Technical-Productive Model: The technical-productive model is based on three components, includes the cultivation method, implementation, and assessment. The first involves diagnosing the current harvesting system, analyzing artisanal practices, biomass availability, ecological conditions of harvesting sites, and socio-economic factors affecting fishers, to identify constraints and opportunities for sustainable development. The second component proposes a productive transformation through a long-line suspended culture system inoculated with laboratory-formed SADs (Spore Adhesion Discs). It incorporates a 2–3 month growth cycle, unit yield estimates, annual harvest frequency, production planning, and environmental parameters of the La Ramada coastal zone (temperature, salinity, dissolved oxygen, fouling, and nutrients), ensuring technical and biological feasibility. The third component consists of a preliminary impact assessment evaluating potential ecological impacts of the model on the marine ecosystem and the fishing community. Factors such as estimated losses due to adverse environmental conditions, biomass fluctuations, and the integration of fishers through training and formalization are considered. This assessment allows for projecting the economic, social, and ecological benefits of implementing the system, as well as identifying necessary adjustments to minimize risks and maximize the sustainability of the culture.

5) Community Integration: The active participation of artisanal fishers has been coordinated; technical training has been provided by CITEpesquero Piura, and the productive organization and formalization of APDAR has been promoted.

III. Results and Discussion

1) Resource Dynamics and Extraction Pressure: Analysis of the *Chondracanthus chamissoi* resource on the northern coast of Peru, using the DPSIR approach, reveals high extraction pressure associated with domestic demand, prices, and an increasing number of fishers. This pressure increases fishing effort and generates fluctuations in available biomass (State), producing economic and social impacts such as income losses exceeding USD 1,900/year and high levels of informal fishing (>50%), which in turn fosters conflicts among fishers [8]. Furthermore, the resource's biomass and density exhibit marked natural variations (140–330 individuals/m² and 0.05–0.83 kg/m²), hindering its sustainable management under open access regimes [8]. Environmental factors, including hydrological variations and ENSO events, further modulate resource availability, highlighting the need for integrated management strategies that incorporate anthropogenic pressures and climate variability [8].

2) Biological and operational viability: Long-line suspended culture, using units inoculated with secondary fixation discs (SADs), allowed for uniform biomass growth to reach a commercial size of ≥8 cm in a 2–3 month production cycle, consistent with previous studies by [11].

TABLE III
Estimated Production of C. Chamissoi by Campaign and Batch

Cultivation system	Number of thallus fragmentation per system	Production cycle (months)	Average yield per thallus fragmentation (kg)	Total production per batch (kg)	Estimated annual production (kg/batch)
Long-line 1	100	2	0.5	50	480–9600
Long-line 2	100	3	0.7	70	480–9600
Long-line 3	100	2–3	0.5–0.7	50–70	480–9600

Vegetative propagation from selected fronds showed survival rates exceeding 85%, indicating that the technique ensures the viability of the resource and reduces pressure on natural populations. Monitoring fouling and nutrients in the open sea demonstrated the need for periodic interventions to guarantee optimal growth conditions, especially during seasonal fluctuations in temperature and salinity. This finding coincides with Wu et al. [15], who reported that regular cleaning of suspended lines improves nutrient uptake and maximizes productivity in commercial macroalgae. The use of natural and artificial substrates for the formation of suspended aquaculture systems (SADs) showed good adhesion and vegetative development, reinforcing the technical feasibility of the proposal. The replicability of the operational flow, SAD formation, inoculation, open-sea growth, harvesting, and post-harvesting, allows for the expansion of the system to different coastal sites with similar characteristics.

3) Technical Viability of the Suspended Culture Model: Laboratory results and recent experiences confirm the technical viability of vegetative propagation of *C. chamissoi* using secondary fixation discs (SADs), an effective method for generating new individuals from vegetative tissue, as demonstrated in Peruvian experimental studies [3]. This approach validates the design and validation of the proposed technical production model for the formation of inoculated units in the laboratory and their transfer for open-ocean cultivation. Long-line suspended culture systems are one of the most widely used and effective cultivation strategies for commercial species. They maximize access to light and nutrients, reduce fouling accumulation, and facilitate operational management in open marine conditions [15], as they improve production yield and sustainability when implemented with proper environmental management and operational maintenance [15]. This sector is experiencing rapid global growth due to its nutritional, socioeconomic, and environmental benefits for local communities, although it faces significant challenges in pollution control, bioaccumulation of contaminants, and crop management [6].

4) Economic Evaluation and Impact Projection: The prospective economic evaluation of the proposed production model, based on the projected cost and revenue data from your study, shows that under the current production scenario using suspended systems and estimated volumes of 480–9600 kg/year, the financial indicators (NPV and IRR) are negative. This indicates that, with the current production scale and operating prices, the project will not achieve profitability within the evaluated timeframe (5–10 years). This result coincides with the financial analysis conducted in your own study, where the cumulative cash flow projection shows extended negative balances throughout the ten years of operation, with a negative economic NPV and an IRR lower than the established discount rate.

TABLE IV
Summary of Production and Financial Indicators

Scenery	Annual production (kg)	Projected price per kg (USD)	Estimated annual income (USD)	5 years (USD)	IRR (%)	B/C ratio	Equilibrium point (kg)
Conservative	480	5	2,400	-1,200	3	0.8	600
Moderate	2,400	5	12,000	500	11	1.2	1,500
Optimistic	9,600	5	48,000	12,000	25	2	4,500

However, this assessment does not invalidate the biological feasibility or the socioeconomic utility of the proposal. Rather, it reinforces the need for production scaling, product diversification, and value-added strategies (for example, extraction of carrageenan or high-value functional ingredients) to improve profitability and make the model a viable alternative for seaweed-harvesting communities. Studies of commercial cultivation of *C. chamissoi* in other areas (such as San Andrés – Pisco) have shown that production models adapted to specific conditions can achieve positive results in economic evaluation indicators, although these depend on a suitable cultivation design and market conditions [16].

5) Socioeconomic Impact: The integration of fishers through APDAR and the technical training promoted by CITEpesquero Piura strengthen community organization and allow for the formalization of the activity, reducing informality and increasing income stability. At the operational level, the model projects a maximum production of 9,600 kg per season and annual production growth from 72,368 kg to 156,779 kg over a ten-year period. However, the estimated revenues, ranging from S/. 31,200 to S/. 67,592.10, are insufficient to cover operating costs, resulting in negative cash flows, with a net present value (NPV) of -S/. 672,740.90 and an internal rate of return (IRR) of -4.88% (Note: Exchange rate used: 1 USD = S/ 3.75 Peruvian soles). These results indicate that, with three cultivation lines, the project is not profitable in the short or medium term. Nevertheless, it is technically feasible; therefore, expanding to twelve cultivation lines is recommended to improve profitability and ensure long-term economic viability [6]. It is necessary to scale up sea production by increasing suspended cultivation lines from 3 to 12 and expanding the laboratory with 16 additional fiberglass tanks, in order to sustain 9,600 kg per season and improve financial indicators, reversing the negative NPV and IRR to achieve medium-term profitability.

6) Environmental impact and sustainability: Suspended cultivation of *C. chamissoi* contributes to mitigating the extractive pressure on natural populations, promoting the conservation of coastal ecosystems. Furthermore, the absorption of dissolved nutrients and carbon sequestration represent additional ecosystem benefits, aligned with environmental sustainability strategies and ecosystem services described by [6]. Analysis under the DPSIR framework demonstrates that the implementation of controlled aquaculture systems allows for the management of fishing pressures and improves the status of the resource (density and biomass), reducing negative economic and social impacts on fishers [8]. The integration of community management measures strengthens socio-ecological resilience and ensures medium- and long-term sustainability.

7) Technical Considerations and Projections: The proposed technical-productive model incorporates three key components: diagnosis of the extraction system, productive transformation through suspended aquaculture, and a preliminary impact assessment. Technical assumptions, such as growth cycle, harvest frequency, and average yield, allow for projecting annual production and estimating losses due to environmental factors, ensuring efficient and realistic planning. The combination of these factors: biological, economic, and social; suggests that the implementation of suspended culture systems represents a comprehensive strategy to stabilize the supply of *C. chamissoi*, strengthen local value chains and promote sustainable coastal development, aligned with the principles of circular economy and biorefinery applied to macroalgae [13].

TABLE V
INTEGRATED INDICATORS FOR SUSPENDED CULTURE OF *CHONDRACANTHUS CHAMISSOI* IN LA RAMADA, PERU

Component	Indicator	Value/Description	Reference/Observation
Biological	Type of crop	Suspended in line (long-line)	[11]
	Propagation method	Vegetative (SADs)	[14]; [3]
	Production cycle	2–3 months per season	Field studies
	Average performance	0.5–0.7 kg/ thallus fragmentation	Projection based on SADs
	Commercial size	≥8 cm	Harvest Requirements
Environmental	Fouling monitoring	Regular cleaning and monitoring	Maintains optimal nutrient absorption
	Physical and chemical conditions	Temperature, salinity, dissolved oxygen	Coastal Zone La Ramada
	Ecosystem impact	Reduction of extraction pressure, carbon sequestration	[8]
Socioeconomic	Community integration	Active participation of APDAR, technical training	CITEpesquero Piura
	Formalization	Regulated association for crop management	Improves revenue and sustainability
	Estimated annual production	480–9,600 kg/year	Based on batch and production cycle
	Projected annual income	USD 2,400–48,000	Projection based on price/kg
	5-year NPV	-1,200 a 12,000 USD	Discount rate 9%
	IRR	3–25%	Different production scenarios
	Break-even point	600–4,500 kg	Based on production scenario
Productive/Operational	Cultivation stages	Formation of SADs, inoculation, growth, harvesting, post-harvest, marketing	Comprehensive production flow
	Substrates used	Natural (shells) and artificial	Guarantees adherence and growth
	Batch per year	2–4 seasons	Production optimization

8) Community Integration and Governance: The socio-productive results of the study show that the integration of artisanal fishers through the La Ramada Artisanal Fishers Association (APDAR) and the technical training provided by the Piura Fisheries Technology Center (CITEpesquero Piura) strengthen community organization and the formalization of aquaculture activities.

This constitutes a key social response for improving cohesion, the management of access rights, and the capacity for dialogue with public and private institutions. This participatory approach addresses one of the weaknesses identified by Atoche Suclupe et al. [8], related to high levels of informality and the lack of community management mechanisms, which contribute to socioeconomic conflicts and uncontrolled extractive pressures. The incorporation of technical training and productive organization processes represents a practical response that can improve the sustainability of the system both biologically and socially [8]. See Fig. 1.

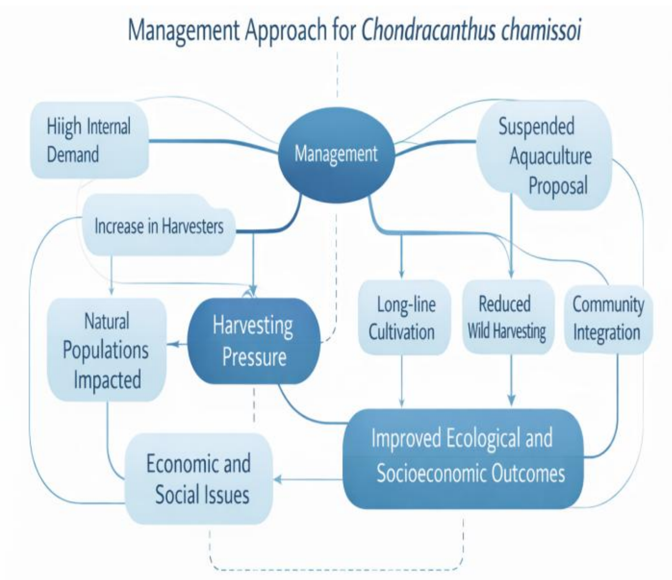

Fig. 1 Reduced pressure of natural populations

CONCLUSIONS

The research demonstrates that implementing a technical-productive model based on vegetative propagation and longline suspended cultivation of Chondracanthus chamissoi is a viable and sustainable strategy associated with its traditional harvesting use. The results confirm the technical viability of the cultivation system, with favorable growth rates, a high survival rate, and efficient biomass production under controlled conditions and in open-sea conditions. From an environmental perspective, the proposed model contributes to reducing extractive pressure on coastal seagrass meadows, conserving and improving ecosystem services, including nutrient absorption, and carbon sequestration. The analysis based on the DPSIR framework supports the use of controlled aquaculture systems and promotes improved biomass and density status by mitigating the impacts of overexploitation and informal practices. The economic assessment shows that the current, conservative production level does not guarantee immediate profitability; however, the model demonstrates significant potential when combined with increased production, value-added strategies, and market diversification. Integrating artisanal fishers through the APDAR program and providing technical training will be key to strengthening community organization, formalizing their operations, and improving their socioecological resilience, all within a sustainable coastal development framework. Future efforts should focus on optimizing economic performance, strengthening governance frameworks, and expanding the model to other coastal areas with similar environmental and social conditions, subject to long-term validation.

ACKNOWLEDGMENT

The authors thank the "Universidad César Vallejo University-Investiga UCV" for their financial support.

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